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Economic Analysis of CO_2 Separation from Coal-fired Flue Gas by Chemical Absorption and Membrane absorption Technologies in China

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Abstract

Two typical CO_2 chemical absorption processes using MEA and aqueous ammonia (AA) solutions to act as absorbents and one novel process using hollow fiber membrane contactors (HFMCs) to act as absorber and MEA as absorbent were analyzed in this study to find out what CO_2 capture process may be more suitable for China. An ultra supercritical PC power plant with 840-MWe-gross-output was selected as the reference case without CO_2 capture. Economic results show that when membrane price is set at RMB 50/m^2 and lifetime is 5 years, CAPEX of MEA, HFMC and AA cases are increased by about 90.12%, 85.4% and 68%, respectively, compared to reference case. And the corresponding cost of avoided is RMB 305.1/tCO_2, RMB 266.45/tCO_2 and RMB 206.02/tCO_2, respectively. The seemingly positive results imply that AA-based chemical absorption process should be the best for China nowadays. In addition, prospect of HFMC process in the future was also considered based on the increasing anxiety of NH_3 slip for AA process. If membrane price can be reduced to less than RMB 20/m^2 and new solvents with ~3 GJ/tCO_2 total regeneration heat requirement can be adopted in the future, HFMC may replace the AA-based method to capture CO_2. Additionally, economic results also show that the development of new solvents only considering the reduction of heat of CO_2 absorption may be not sufficient in terms of the reduction of CO_2 avoided cost. That is because CO_2 avoided cost can only be reduced by about 8% even the heat of CO_2 absorption can be reduced by about 60%. Finally, effects of coal price, improvements of reference case and CO_2 capture system on the cost of CO_2 avoided were also investigated.

Keywords: CO_2 capture; Hollow fiber membrane contactor; Economics; Power plant;

1. Introduction

In the near future, carbon capture and storage (CCS) may be the most effective method to trim CO_2 emissions in a large scale. Among all the applicable CO_2 capture technologies, monoethanolamine (MEA) based CO_2 chemical absorption process always was considered as the currently most promising for CO_2 capture from flue gas due to its

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so longer successful commercial implications [1]. However so many economic analyses on CO_2 capture using MEA showed that investment of PC power plant and cost of electricity (COE) will increase considerably after the integration of CO_2 capture and compression, resulting in the unacceptable cost of CO_2 avoided [2,3]. Increment of investment and COE was considered as the result of high energy requirement for MEA-based CO_2 capture system, especially higher CO_2 regeneration heat requirement [4].

Now membrane CO_2 absorption technology and CO_2 chemical absorption method using aqueous ammonia may be the alternative to reduce CO_2 capture investment and CO_2 cost due to their exclusive advantages. Hydrophobic hollow fiber membrane contactors (HFMCs) is only used to act as the permeable barrier between gas and liquid phase in membrane CO_2 absorption technology due to its high specific surface area than packings, and CO_2 is captured by solvents. So membrane CO_2 absorption technology has the potential to reduce the size of absorber and desorber [5]. In addition, membrane CO_2 absorption technology can also solve the operating problems successfully including entrainment, flooding and foaming, which means that solvent losses can be reduced substantially, thereby reducing the absorbent makeup cost. Therefore membrane CO_2 absorption technology is considered by many researchers as the suitable alternative to chemical absorption technology [6]. Additionally some unique problems existing in membrane CO_2 absorption technology including membrane wetting and plugging should be paid more attention due to its negative or destructive effect for CO_2 capture [7].

Furthermore, CO_2 chemical absorption technology using aqueous ammonia (AA) solution to absorb CO_2 in absorber was considered as another alternative to replace MEA-based technology due to its larger CO_2 loading capacity and lower regeneration energy requirement than MEA [8,9]. These positive results seemingly show that AA process can get the lowest CO_2 avoided cost. And many researchers also reported the similar results [10]. However although some so-called effective methods were investigated [11], the highly volatile nature of ammonia may still be the major obstacle for the implications of AA process.

As for the developing country, China should select these CO_2 capture technologies with low investment and low CO_2 avoided cost for the reduction of large quantity CO_2 emissions in future. So a comprehensive economic comparison among CO_2 capture using MEA, AA and the combination of hollow fiber membrane contactors and MEA will be executed in this study to select the acceptable CO_2 capture technology for China. And the prospect of membrane CO_2 absorption technology will also be discussed.

2. Methodology

2.1. The case study

2.1.1. Reference case and study basis

An ultra supercritical PC power plant with 840 MWe gross output was selected to act as the reference case to analyze the effect of different CO_2 capture technologies on the capital expenditure (CAPEX), COE and cost of CO_2 avoided. The main steam conditions of PC power plant are 29 MPa/600ºC/620ºC and steam cycle flow diagram was designed to be same to reference [12]. The total mass flow rate is about 894 kg/s, and CO_2 concentration is about 13.31 vol.%. In this study, the gross output of plant without or with CO_2 capture is maintained 840 MWe, which means that the coal feed rate is constant no matter whether CO_2 is or not captured. SO_X and NO_X concentration in the flue gas should be limited by ESP and WFGD methods to achieve the corresponding Chinese emission standard, respectively. The main criteria for economic analysis can be found in Table 1.

2.1.2. MEA case

CO_2 capture using MEA-based chemical absorption process (MEA case) is shown in Fig. 1. As for MEA case, random packed columns will be used to act as the absorber and stripper. In this study, 30 w.t.% MEA is selected to absorb CO_2. In addition, the CO_2 loading value of lean solution is set about 0.25 molCO$_2$/molMEA to get the lowest regeneration energy consumption based on the useful results reported by the researchers [13]. And the CO_2 loading capacity of MEA is determined to about 0.054 kgCO$_2$/kg solution [14].The absorption temperature is designed at 40 ºC and average pressure is about 1.13 bar. The regeneration temperature is 120 ºC and pressure is 2.1 bar. So relying on these operating conditions, size of absorber and stripper can be determined based on the model provided by Abu-Zahra et al. [3].

Table 1 Study basis and some economic data in this study.

Project life (years)	25
Construction period (years)	3
CAPEX distribution	20% for the first construction year; 45% for the second year; 35% for the last year
Load factor	63.75% for the first operating year; 85% for the other years
Nominal discount rate	10% without considering inflation
Coal type	Chinese Shenhua bituminous coal (LHV: 22.76 MJ/kg)
CO_2 capture efficiency (%)	90
CO_2 product temperature (ºC)	50
CO_2 product pressure (MPa)	15
Coal price (RMB/GJ)	16
MEA price (RMB/t)	20000
Liquid ammonia price (RMB/t)	3000
Membrane price (RMB/m2)	50
Water price (RMB/t)	0.2 for cooling water; 1 for industrial water

Steam will be extracted to regenerate CO_2 in the reboiler from the LP turbine in the power island. In order to prohibit MEA degradation rates and corrosion problems, heating saturated steam in the reboiler is set at about 130 ºC [12]. And in the reboiler the heating steam is only condensed to transfer its latent heat to MEA rich solution and becoming the saturated condensate, i.e. no pressure drop and temperature fall will be occurred in the reboiler. Then saturated steam with 140 ºC and 361 kPa will be extracted from the LP turbine. In addition, CO_2 compression heat will be recovered to heat the condensate coming from turbine in the intercoolers to raise its temperature and increase the power output, as shown in Fig. 1. Recovery of CO_2 compression heat can be found elsewhere [12,15].

2.1.3. HFMC case

The only difference between CO_2 capture process by using hollow fiber membrane contactors and MEA (HFMC case) and packed columns (MEA case) is the type of absorber. The hollow fiber membrane contactors are adopted and elaborately arranged to replace the random packed columns as the absorber. In this study hydrophobic PP membranes are selected because of its relatively lower price and commercial availability. The inner diameter (I.D.) of PP fiber is 300~400 µm, outer diameter (O.D.) of fiber is 400~500 µm and the porosity of the fiber is about 50%.

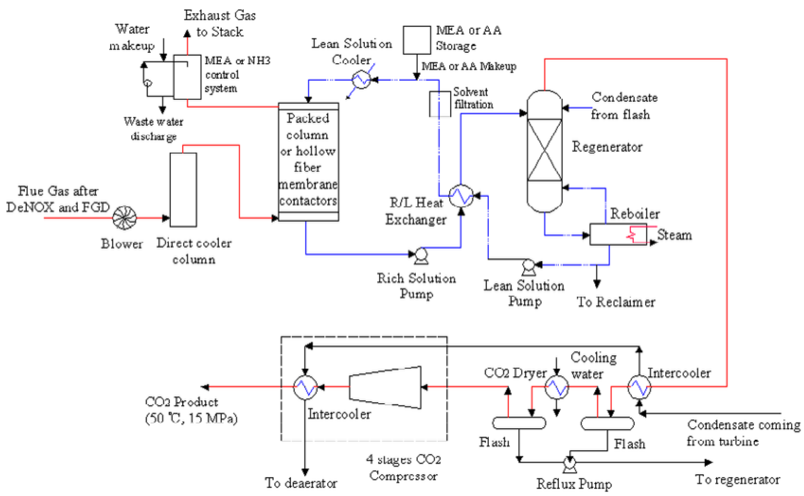

Fig. 1. CO_2 capture and compression process by using MEA, AA or HFMC process.

In order to prevent the membrane wetting problem it is preferable to decrease the MEA concentration due to the contradiction between surface tension of solution and MEA concentration. But lower MEA concentration will compromise the CO_2 removal efficiency, leading to an increase in the flow rate of the solvent and consequently an increase in regeneration energy consumption. In addition, if the pressure difference between liquid and gas phase can be regulated gently to less than the breakthrough pressure and membrane contactors can be renewed frequently after some appropriate times, the membrane may still run wonderfully. So 30 w.t.% MEA is still selected in this case. In order to compare to MEA case all the operating parameters of absorber, stripper and reboiler are designed as same as MEA case. But for HFMC case, the key parameter is the total liquid-gas contact area or the total membrane inner surface area. Due to the constant liquid-gas contact area the total membrane contact area can be linear scaled-up easily based on some successful projects or even the experimental results. In combination with the successful experimental results using different membranes [16,17] and mass transfer model [18], the total membrane contact area can be calculated.

2.1.4. AA case

Table 2 CAPEX estimating method.

Description	Type	Value
Direct material cost (DMC)	Input	Assessment
Construction cost (CC)	Input	Assessment
Direct field cost (DFC)	DFC = DMC + CC	
Construction management	Input	2% DFC
Commissioning	Input	2% DFC
Commissioning spares	Input	0.5% DFC
Temporary facilities	Input	5% DFC
Freight, taxes&insurance	Input	1% DFC
Indirect field costs (IFC)	IFC=sum of above from (construction management) to (freight, taxes&insurance)	
Engineering cost (EC)		12% DFC
Total installed cost (TIC)	Output	TIC=DFC+IFC+EC
Contingences	Input	10% TIC
Owners cost	Input	7% TIC
CAPEX	Output	CAPEX=TIC+Contingences+Owner cost

Like MEA case, ammonia-based CO_2 capture process (AA case) also selects the packed columns to act as the absorber and stripper. In this study 14 w.t.% AA solution is selected, and absorption temperature is selected about 33~35 ºC based on the compromise between the reaction kinetics [19] and energy requirement for cooling flue gas. The CO_2 loading capacity is set at 0.068 $kgCO_2/kg$ solution when NH_3 slip is considered [14]. In order to control NH_3 slip coming from the absorber, NH_3-control packed column under the circulating washing water is adopted, which is cited from reference [20]. In addition, high regeneration pressure and temperature should be selected to prevent NH_3 slip in the regenerator. So the temperature is set at about 120 ºC and the corresponding regeneration pressure is determined at about 40 bar [8]. Then steam with 148 ºC temperature and 451 kPa pressure will be extracted from turbine to heat the rich AA solution in the reboiler.

2.2. Cost analysis model

2.2.1. CAPEX estimation

CAPEX for all the cases in this study will be estimated using the methodology adopted widely in references [13], as shown in Table 2.

2.2.2. Annual operating cost model

Annual operating costs consist of three parts: coal costs, fixed operation and maintenance (O&M) costs and variable O&M costs. Coal costs can be calculated by multiplying coal price and the total coal flow rate. O&M costs can be estimated by the method shown in Table 3. Unlike the other cases, membrane renewable costs should be added into the fixed O&M costs for HFMC case to prevent the membrane wetting and plugging problems. Chemicals and consumables costs include solvent makeup costs, inhibitor additive consumption costs, NaOH consumption costs used in the reboiler, activated carbon costs used in the solvent filter, limestone consumption costs and water makeup costs.

2.2.3. Calculation model of COE and Cost of CO_2 avoided

COE can be calculated based on a zero net present value (NPV) of the operating and CAPEX over the project life [15]. And CO_2 avoided cost can be determine by the following equation:

$$CO_2 \text{ avoided cost} = \frac{\left\{(\mathrm{COE})_{\mathrm{capture}} \text{-} (\mathrm{COE})_{\mathrm{ref}}\right\} \mathrm{RMB/MWh}}{\left\{(\mathrm{Emissions})_{\mathrm{ref}}^{\mathrm{CO_2}} - (\mathrm{Emissions})_{\mathrm{capture}}^{\mathrm{CO_2}}\right\} \mathrm{tCO_2/MWh}} \tag{1}$$

Table 3 Calculating method for O&M costs.

Parameters	Units	Reference case	MEA case	HFMC case	AA case
Maintenance costs	MRMB/yr	4% CAPEX			
Insurance and taxes	MRMB/yr	2% CAPEX			
Operating labor costs	MRMB/yr	Multiplying by operator numbers and a operator salary per year			
Operator labor overhead and supervision	MRMB/yr	30% of operating labor costs			
Catalyst renewable cost in DeNOX	MRMB/yr	Calculating			
Membrane renewable costs	MRMB/yr	0	0	Membrane investment divided by membrane lifetime	0
Fixed O&M costs	MRMB/yr	Sum of 6 items above.			
Variable O&M costs	MRMB/yr	Including chemicals and consumables costs and waste disposal costs (RMB 30/t for liquid waste and RMB 100/t for solvent waste)			

3. Economic results

Table 4 Cost and performance summary in this study.

Parameters	Unit	Reference base	MEA case	HFMC case	AA case
Fuel input	MWth	1826	1826	1826	1826
Gross power output	MWe	840	724.9	724.9	732.7
Net power output	MWe	793.8	588.3	597.14	626.98
Net thermal efficiency	%	43.47	32.22	32.7	34.33
Energy penalty	%	—	11.25	10.77	9.14
Base plant CAPEX	MRMB	4179.36	4179.36	4179.36	4179.36
Capture plant CAPEX	MRMB	—	1709.42	1650.18	1365.82
Total CAPEX	MRMB	4179.36	5888.78	5829.54	5545.18
Specific CAPEX	RMB/kWnet	5265	10009.8	9762.38	8844.24
COE	RMB/MWh	273.24	486.21	459.64	418.44
Cost of CO_2 avoided	RMB/t	—	305.1	266.45	206.02

The economic results using three different CO_2 capture processes are shown in Table 4. The economic simulation about HFMC case is based on the most likely conditions of membrane with RMB 50/m^2 membrane price and 5 years membrane lifetime. It can be seen from Table 4 that AA case has the lowest CAPEX, COE and cost of CO_2 avoided nowadays. That is because AA can possess higher CO_2 loading capacity and lower regeneration heat consumption than MEA. It also can be seen from Table 4 that the economic data of HFMC case are superior to MEA case contributed to the favorable operation and low solvent losses, meaning that using membrane gas absorption process can save the capture investment and reduce CO_2 avoided cost.

In addition, though there are a number of published studies that examine capturing CO_2 from coal-fired power plants, this study will be compared to the reported results [3,10,14,21]. The comparison of economic results is presented in Fig. 2. It can be seen Fig. 2 that costs of CO_2 avoided of MEA case and AA case in this study are only slightly higher than NZEC report which was finished in 2009 based on Chinese situations [13]. The main reason may be that the CO_2 compression pressure (15 MPa) in this study is set higher than NZEC report (11 MPa), which will result in more energy consumed. In addition, CO_2 avoided costs of this study and NZEC report are lower than other AA cases. That is because that AA case cited from NETL report can sell the NH_4HCO_3 by-products as fertilizer to get the revenue, leading to the reduction of CO_2 avoided cost [14]. And for Gal's report [21], chilled ammonia process (CAP) was adopted to control NH_3 slip, and then higher CO_2 loading capacity can be obtained. In addition, the simulation results also showed that flue gas could be easily cooled to the low temperature. Based on these advantages, cost of CO_2 avoided using AA process can be reduced to about \$ 21/tCO_2 [21].

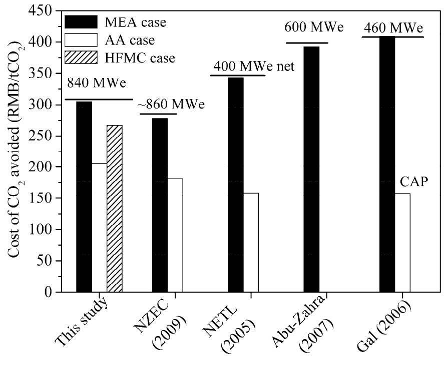

Fig. 2. Comparison of CO_2 avoided costs (1 2005US$=8 2005RMB, 1 2006€=10 2006RMB).

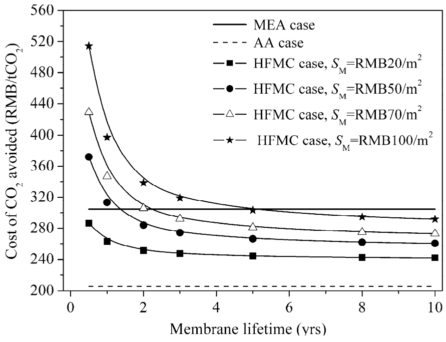

Fig. 3 Effect of membrane factors on CO_2 avoided cost.

But it also can be seen that AA case is superior in CAPEX than HFMC case. The results seemingly show that although membrane absorption process can get lower CO_2 avoided cost than MEA-based process, AA-based CO_2 chemical absorption process may still the best for China nowadays. However it should be worthy to note that a higher membrane price is selected in this study, leading to the higher CAPEX. It is well-accepted that lower membrane price will result in the lower CAPEX of HFMC case, and then the lower CO_2 avoided cost. And when the membrane price can be reduced to an appropriate value, new solvents with lower regeneration heat consumption can be adopted and human and environmental tolerance focusing on NH_3 emission is less in the future, can it be hypothesized that membrane gas absorption process will compete with AA process in the future? So the prospect of HFMC case should be assessed.

4. Sensitivity analysis

4.1. Prospects of HFMC case

4.1.1. Effect of membrane factors

Effect of membrane price and membrane lifetime on cost of CO_2 avoided is plotted in Fig. 3. It can be seen from Fig. 3 that lower membrane price can result in lower CO_2 avoided cost at any membrane lifetime. That is because the reduction of membrane price can lead to the reduction of the total CAPEX through reducing the investment of absorber and the reduction of fixed O&M costs by reducing the membrane renewable costs. In addition, increase of membrane lifetime can also result in the reduction of CO_2 avoided cost because of the reduction of membrane renewable costs as membrane lifetime rises. So the lower cost of CO_2 avoided can be obtained by lengthening the membrane lifetime. However longer membrane lifetime in the operations should need more stringent and effective methods to prevent the membrane wetting and plugging problems, which will lead to the significant additional O&M costs, as shown in Fig. 3.

It is very important for us to note that even though very lower membrane price and so longer membrane lifetime are adopted in the simulation, AA-based CO_2 capture is still less expensive.

4.1.2. Effect of CO_2 solvent improvement

It can be seen from Fig. 3 that even membrane price may be reduced to RMB 20/m^2, AA case is still less expensive when MEA is still adopted to act as the CO_2 absorbent. If HFMC case wants to compete with AA case in the future, new solvents must be developed. Many researchers are now working on developing new or blended solvents which have the same CO_2 absorption as MEA and lower heat of CO_2 absorption in order to replace MEA. So this study has also examined cases adopting such new solvents with the maximum 60% improvement in heat of CO_2 absorption compared to MEA. The cost of CO_2 avoided sensitivity to solvent improvement is shown in Fig. 4.

As shown in Fig. 4, new solvents with 70% heat of CO_2 absorption compared to MEA are feasible and may be obtained from some suppliers in the near future. Adopting these new solvents, the cost of CO_2 avoided for MEA case can only be reduced by about 8%. And even heat of CO_2 absorption can be reduced by about 60% for the new solvents compared to MEA, CO_2 avoided cost can be reduced only by about 16.3% for MEA case. So the researches of new solvents only concerning the reduction of heat of CO_2 absorption may be not sufficient in the future in terms of greatly reducing the cost of CO_2 avoided. And the new solvents leading to the great reduction of total regeneration heat consumption (TRHC) may be viable in the future.

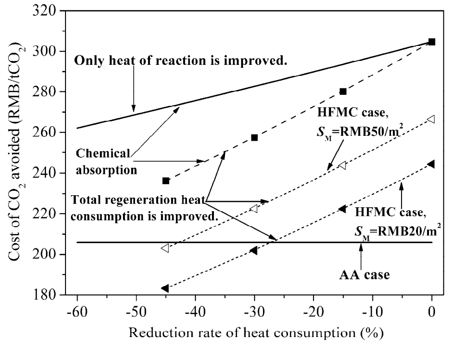

Fig. 4 Effect of improvement in solvent performance on CO_2 avoided cost.

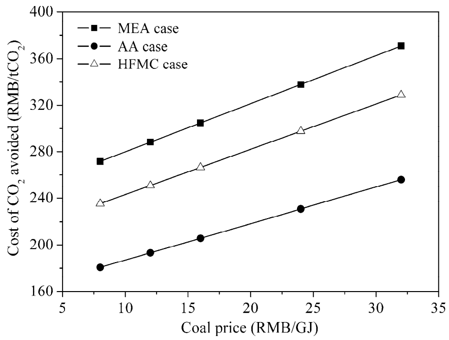

Fig. 5 Effect of coal price.

As shown in Fig. 4, effect of reduction of TRHC on CO_2 avoided cost is also studied in this study. Reduction of TRHC by using new solvents can result in the great reduction of CO_2 avoided cost. And HFMC case can compete with, even superior to AA case when these new solvents adopted in the future. When membrane price can be reduced to RMB 20/m^2 and new solvents with 30% improvement in TRHC (~3 GJ/tCO_2) compared to MEA can be adopted in the future, HFMC case will be less expensive than AA case.

4.2. Sensitivity analysis

4.2.1. Economic variables

In this study, like the method reported by Singh et al. [2], two economic parameters affecting the cost of CO_2 avoided were discussed. The first is coal price, which can be quite volatile in the future. The second variable is changes in the CAPEX estimation of reference base plant. Effects of these two variables on CO_2 avoided cost are shown in Fig. 5 and Fig. 6, respectively. It can be seen from Fig. 5 that cost of CO_2 avoided for all the three cases increases linearly with the coal price because of the increase of coal cost in the annual operating cost. The results show that the cost of CO_2 avoided will increase inevitably and be expensive than now due to a decrease in coal reserves. However it also can be seen from Fig. 5 that the resulting increment in CO_2 avoided cost is relatively insensitive to coal price. A tripling of coal price from RMB 8/GJ to RMB 24/GJ only results in the cost of CO_2 avoided increase of about 26.5% for HFMC case.

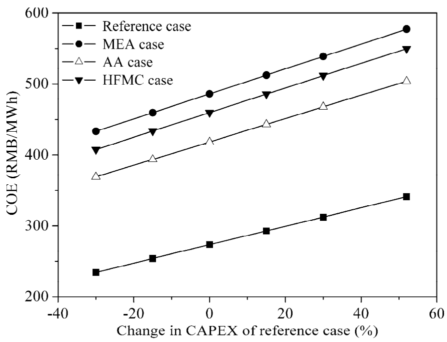

Fig. 6 Effect of reference case CAPEX.

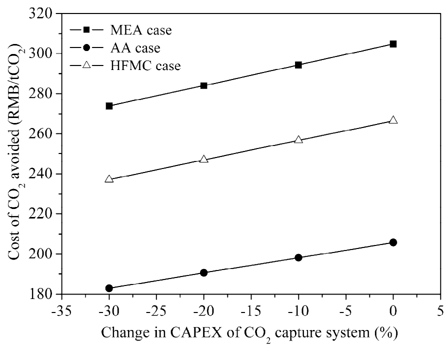

Fig. 7 Effect of CO_2 capture system improvement.

Fig. 6 shows the sensitivity curves for all the three cases when the accuracy of the estimating CAPEX of base plant is changed from -30% to 50%. The *x*-axis represents the percent change of base plant CAPEX. The AA case is slightly more sensitive to the CAPEX of reference case than others, since the proportion of base plant investment to total CAPEX for AA case is highest. In addition, it is apparent from the data that all the lines are relatively parallel and linear. The results imply that CO_2 avoided cost can be reduced in the future due to the improvement of reference case even other factors can not be changed.

4.2.2. Research-driven variables

Two research-driven variables including amine solvent improvement and CO_2 capture system improvement are also investigated in this study, which are shown in Fig. 4 and Fig. 7, respectively. In the future improvements in CO_2

absorber and stripper or will reduce CAPEX of CO_2 capture system directly. For example, if rotating packed bed (RPB) or novel CO_2 regeneration process can be adopted in the future for MEA case or AA case, the CAPEX will be reduced due to the reduction of absorber or stripper size. In addition, if new membrane contactors contributing to the increase of mass transfer efficiency of CO_2 absorption can be obtained, membrane contact area will be reduced greatly, which may lead to the great reduction of CAPEX of HFMC case. As shown in Fig. 7, CO_2 avoided cost will be reduced linearly as CAPEX of CO_2 capture system reduces, as expected, since the lower CAPEX of CO_2 capture system will lead to the lower total CAPEX and lower fixed O&M cost, therefore the lower cost of CO_2 avoided.

5. Conclusion

An ultra supercritical PC power plant with 840-MWe-gross-output was selected as the reference case in order to assess the influence of CO_2 capture using three typical CO_2 capture systems such as MEA-based, AA-based chemical absorption processes and membrane CO_2 absorption process. Results show that CO_2 capture using AA solution nowadays is cheapest among all the three CO_2 capture technologies. Cost of CO_2 avoided is about RMB 205.8/tCO_2 for AA case. CO_2 capture using membrane absorption process is still less expensive than MEA case even membrane price is higher. In addition, prospect of membrane absorption process in the future was investigated in this study. When membrane price can be reduced to less than RMB 20/m^2 and new solvents whose total regeneration heat consumption is lower than 3 GJ/tCO_2 can be adopted in the future, cost of CO_2 avoided can be reduced to less than RMB 200/tCO_2. The results show that membrane CO_2 absorption process will have the opportunity to replace the other processes to capture CO_2 from coal-fired flue gas in the future.

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